THE METEOROLOGICAL PART IN THE EUROPEAN PROJECT DELICAT
DEmonstration of LIdar based Clear Air Turbulence

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1. CLEAR AIR TURBULENCE

Clear-air turbulence (CAT) is atmospheric turbulence encountered outside thermal front regions and outside convective clouds. It is encountered mostly at higher altitudes, from 500 hPa up to the tropopause, in cloudless atmosphere or inside thin cirrus clouds. It may nevertheless create considerable problems for air traffic. It is based on rather complex physic processes and may have various causes. Forecasting this phenomenon is of great practical importance to the aircraft crews but represents a considerable challenge to meteorologists. Most of the practical methods used at the time being are based on empirical approaches. These methods link statistically the observed cases of CAT and some particular features of the atmospheric soundings or synoptic maps. It is mainly related to the presence of the vertical or horizontal shear which is often generated by the jet streams and by frontogenetical processes.

2. DELICAT – THE PROJECT

Atmospheric turbulence encounters are the primary cause of injuries to passengers and flight crews in non-fatal airline accidents. A whole class of turbulence, responsible for 40% of turbulence accidents, and designated as Clear Air Turbulence, cannot be detected by any existing airborne equipment, including state-of-the-art weather radar. This explains why the number of turbulence accidents has been growing by a factor of 5 since 1980, 3 times faster than the increase of the air traffic.

To improve the onboard detection of CAT, the DELICAT (DEmonstration of LIdar based Clear Air Turbulence) project has been funded by the seventh framework program (FP7) of the European Commission. Thirteen partners representing various fields of activity, research centers, industries, universities, and meteorological centers are involved in this project for a period of three years (2009-2012).

The objective of DELICAT is to validate the concept of LIDAR based medium range (10 km to 30 km) turbulence detection which allows securing of passengers and crewmembers by seat belts fasten.

The validation of medium range turbulence detection is based on the comparison of the information on a turbulent atmospheric area, provided on one side by the remote UV LIDAR and on the other side by the aircraft sensors (acceleration, air speed, temperature). This validation includes the following steps:

- A UV LIDAR mock up is designed and manufactured, tested in laboratory on the ground, and then installed onboard a research aircraft, which is intended to fly in turbulent and non-turbulent conditions

- During the flight tests, the atmosphere is analysed by the UV LIDAR and also by the aircraft onboard sensors

- The data obtained from the LIDAR and from the aircraft sensors are compared off line once the aircraft on the ground. The correspondence between LIDAR backscattered energy fluctuations and turbulence experienced by the aircraft, for a given atmosphere area, is assessed and evaluated.

Along the project, the meteorological expertise is brought by Météo-France and ICM (Interdisciplinary Centre for Mathematical and Computational Modelling - Warsaw University). The flight test preparation includes selection of the best places and times of the year where turbulence conditions are expected to be found. To answer the question about best locations and season, climatologies have been calculated. The CAT indices chosen to compute this climatology are ELLROD (1 and 2) indices. They have been calculated for each month for different vertical flight levels on a global scale, as well as on a focus over Europe. Those climatologies were compared with short term wind speed climatology covering North Atlantic and Europe based on the COAMPS NWP model.

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3. CLIMATOLOGIES

To support the choice of the best locations and periods for the flight test campaign, CAT indices climatologies have been elaborated by using among others, the ECMWF (European Centre for Medium-Range Weather Forecasts) ERA-Interim reanalysis database (1989-2008). It is completed with short term (2008-2010) wind speed climatology covering North Atlantic and Europe based on the COAMPS ver. 3 NWP model.

3.1. Climatology based on the reanalysis ERA-Interim

The operational NWP models constantly improve, taking benefit from the constant evolution of the scientific community abilities, in terms of research, of computing capacities, observing systems. The assimilation system continues to improve steadily, taking into account every new piece of information and its implementation in the operational NWP suite.

To be able to benefit from these evolutions, periodically, new reanalysis are calculated. At a specific moment, the state of the art NWP and assimilation scheme are used with the archived observation dataset, therefore allowing the use of all possibly available observation data. Then successive reanalyses, describing the state of the atmosphere at given times, are available with a better homogeneity as they are calculated with the same assimilation system.

Recently a new reanalysis has been calculated by the ECMWF (European Centre for Medium-Range Weather Forecasts). It has been computed on the period from 1989 to 2008 on a global scale with a spatial grid resolution of 0.5 degree.

Methodology:

Two CAT indices have been calculated on these reanalyses on the four available networks 00TU, 06TU, 12TU and 18TU. The chosen indices are ELLROD 1 and 2, mostly used by operational forecasters. They are based on horizontal deformation (completed by the convergence term in the ELLROD2 index) and vertical wind shear. Deformation, wind shear and convergence derived from the numerical weather prediction (NWP) model.

The formulas for these indices are presented in the following paragraphs. Details are available in annex.

ELLROD1 :

Ellrod’s index (Ellrod and Knapp 1991, [12]) was defined to indicate the likelihood of encountering shear-induced CAT.
The ELLROD1 index is defined as follows:

ELLROD1= Vertical Wind Shear x Deformation

ELLROD 2 :

The ELLROD2 index is defined as follows

ELLROD2= Vertical Wind Shear x (Deformation + Convergence)

A climatology is calculated for each index, for every month and for the following levels 150, 200, 250, 300, 400, 500 hPa. The results are presented on two geographical domains, the world and a focus over Europe.

As a first stage, the mean, minimum and maximum values are calculated for each month on the six selected levels, for both the two CAT indices.

It is completed by the calculation of the categories frequencies. The following categories have been chosen (in consistency with the selected thresholds used for operational purpose):

- nul/light (ELLROD index lower than 6.10^{-7} sec^{-2}),
- moderate (ELLROD index between 6.10^{-7} sec^{-2} and 24.10^{-7} sec^{-2}), and
- severe (ELLROD index up than 24.10^{-7} sec^{-2}).

The last step was to calculate the 20%, 50%, 80%, 90% and 99% percentiles. To give an example, the 90% percentile provides the value taken when 90% of the cases of the sample (in this case 20 years of indices, 4 times a day) are below and 10% of the cases above the indicated value. These data, displayed as maps, allow representing the highest CAT index values that can be taken for each point

Results:

Climatologies based on ELLROD1 versus ELLROD2 indices are pretty comparable. The most relevant difference, due to the addition of the convergence term in ELLROD2 is that it can slightly increase the values based on ELLROD2, but the difference remains hardly significant.

The three levels 300hPa, 400 hPa and 500hPa are the most relevant, then the general signal get lower on upper levels, still discernible at 250 hPA, and becomes less and less significant on levels 150 hPa and 200 hPa.

Generally, over areas showing significant turbulent signal, the mean values range between 2.10^{-7} sec^{-2} and 4.10^{-7} sec^{-2}. The maximum values maps indicate some events with values more than 8.10^{-6} sec^{-2}. The minimum maps do not give relevant information.

The most representative maps are the moderate class frequencies. Regarding the severe intensity class (indices $>24.10^{-7}$ sec^{-2}), the cases number is too low to be significant.

On a global scale, three big areas stand out. (See figure 1). The first place is located on the southern hemisphere along the latitude 80 degrees during winter (10% of moderate class cases). It moves northward to reach the latitude 20 degrees in summer (30% of moderate class cases).

The second main area is located in the northern hemisphere and covers the CONUS and the North Atlantic Ocean. In winter it extends over the northern Europe. This area gets smaller in surface as it moves towards higher latitudes in summer. It can be seen as well in summertime from the mouth of the St Lawrence to the south of Greenland.

The third main zone is a fine band from 20N to 40N extending from the middle of the Atlantic Ocean, crossing the north of Africa, the northern India and the south of China. It spreads over the Pacific Ocean to join the area on the CONUS by the west. The highest values can be found in the south of China in winter. In summertime, 15% of moderate class cases are concentrated on Central Europe and in the western part of Canada. It can be noticed that on Western Europe, the most frequent cases of moderate class are observed on Great Britain and on Scandinavian countries.

Figure 1 represents the frequency of the moderate class over the globe at 400hPa, for the two most representative months, January and July. The theoretical position of the jets and hits shifting between summer and winter is neatly visible, as expected. Nevertheless additional features can be seen.

Figure 2 and 3 focus on Europe at 400hPa, for January and July. The maximum values are plotted on figure 2. The features representing highest indices could be associated to unique special very severe events. The figure 3 represents the 20%, 90% and 99% percentiles of the ELLROD2 CAT index.

3.2. Climatology based on COAMPS model

It is a widely known fact that CAT is often found in vicinity of jet stream core due to large vertical wind shear (VWS) generating instabilities in the horizontal flow when background conditions are favourable Miles and Howard (1964). In order to complement turbulence index climatology a wind speed climatology has been calculated. The dataset consisted outputs of NWP model COAMPS v. 3 covering North Atlantic and Europe. Horizontal resolution was 39 km with 30 vertical levels and the period covered was from 2008 to 2010.

Simple wind speed monthly mean was calculated as well as variance for respective monthly datasets. Since the aim of the climatology was to find locations where jet stream could be expected to be found as stable as possible variance damping was used as shown below

V_{DAM}=V*exp(-SD/V)

Here V is mean wind velocity and SD is variance of wind velocity.

This refined initially simple and not so precise wind speed climatology to be accurate in finding locations where jet stream could be expected to be found most of the time. As it occurred regions indicated by this climatology were in coincidence as those indicated by climatologies described in section 3.1. This in turn brings the question whether long term index climatologies will concentrate only on preferred jet stream locations and significant orography as being more or less constant over years while loosing most of the subtle features as statistical noise. The climatology Jaeger and Sprenger (2007) hints that indeed this can be expected however no further research was done on this topic as being well outside the scope of the project.

4. E-AMDAR DATA FOR INDICES VERIFICATION

The flight test campaign will give the opportunity to verify the indices previously selected by using all the aircraft sensors data and also the LIDAR measurements.
For a more systematic verification of the developments done in the DELICAT project, the turbulence observed data from the E-AMDAR program will be used.

Within the E-AMDAR program, meteorological parameters measured by onboard sensors of commercial aircrafts are collected.

This meteorological data is transferred to the ground in real-time, using downlink the meteorological network, as text messages called AMDAR (Aircraft meteorological data relay).
Currently, commercial aircrafts are equipped with sensors, which are able to measure temperature, pressure, wind intensity and direction, and geographical position.
The AMDAR message contains these parameters and, in addition, two parameters relevant to turbulence. These last ones are calculated on-board in form of :

- a “Turbulence Intensity” IT (based on the vertical acceleration measured by the aircraft accelerometers and converted in a WMO scale with four values)

- along with a “Derived Vertical Gust” DEVG.

The DEVG represents the vertical gust able to generate at sea level the same acceleration as measured by the accelerometer located at the aircraft centre of gravity. The interest of DEVG value is that it is expected to be independent the aircraft type and characteristics, on the contrary of the IT.

A drawback of AMDAR data is irregular spatial distribution leading to lack of data in large areas such as southern hemisphere and oceanic zones. .

The turbulence information is concentrated around the airports and over busiest air traffic areas.

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Moreover, the data is unevenly distributed in time since the number of AMDARs is dependent on the air traffic volume which in turn changes significantly depending on time. The traffic is concentrated during the daytime, between 6 and 22UTC.

5. CAT FORECASTING DEVELOPMENT AT ICM

Research work at ICM is concentrated in three main directions. First of those is an attempt to construct adaptive regression index (an analogue to Sharman et al. (2006)). Second is aimed at evaluating the possibility of use and the effectiveness of machine learning (namely Random Forest) for CAT forecasting. While the third inspired by Passner and Knapp (2008) is aimed at evaluating various horizontal resolutions influence on CAT forecasting. Each part is verified by E-AMDAR (description TB).

While two latter topics are under development, the first one comes to initial conclusions. The evaluation study was done using January 2007 as 'training period' ie. Regression coefficients were calculated using various CAT indices calculated for this period and E-AMDAR DEVG data. Background NWP model was UM v. 4 covering central Europe with horizontal resolution of 17 km. Resulting index can be understood as predicted vertical wind gust speed. Example result with overlying AMDARS can be seen on Figure 5. In overall this experiment showed poor performance. Possible causes are insufficient data and too long 'training period'. However sequential coefficients updating with reasonable periods might fix those shortcomings.

Another recent development is attempt of new CAT predictor formulation based on gravity waves propagation mechanisms described in Kopeć et al. (2011). This method although giving promising results has not been verified against observation.

6. HIGH VERTICAL NWP MODEL RESOLUTION IMPACT ON CAT INDICES

Most of the CAT indices were designed some years ago with large scale numerical prediction models. The study aim is to evaluate the impact of the increased resolution of the NWP model. The ARPEGE Météo-France NWP model is used. Its newest horizontal resolution is 0.1 degree on the European domain instead of 0.25. Selected CAT indices are calculated on the native vertical resolution of the NWP instead of on the post processed fields. This work is still going on. The verification will be processed by using all data collected during the flight test campaign. A more systematic verification on the AMDAR data base over the first months of the year 2010 is equally on progress.

7. CONCLUSIONS

The ELLROD1 and ELLROD2 climatology calculated on ERA_Interim reanalysis, shows a good consistency with the known positions of the jets axes. The seasonal movement is well represented. This work made on this climatology made clearer the range of possible values of these indices in relation to theoretical jet location.

Another result is about areas likely to be impacted by turbulence, providing helpful information to be used when planning the flight during the DELICAT flight test campaign. Somewhat surprisingly, three year damped wind climatology stood in good agreement with indices study.

Evolution of NWP models and computers ability makes increasing grid resolution possible. Those possibilities can lead to enhanced performance of known CAT indices. Various horizontal and vertical resolutions are considered and will be tested during the project. This work will be completed by development and evaluation of alternative CAT detection algorithms.

8. ACKNOWLEDGMENTS

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9. BIBLIOGRAPHY

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10. EQUATIONS

Input parameters for the CAT index

- Stretching deformation: DST= $\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}$
- Shearing deformation: DSH= $\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}$
- Horizontal Convergence : CVG= $-\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$
- Deformation DEF = $\sqrt{DST^2 + DSH^2}$
- horizontal wind shear: Sh=
$$\frac{1}{u^2+v^2}\left(uv\frac{\partial u}{\partial x} - u^2\frac{\partial u}{\partial y} + v^2\frac{\partial v}{\partial x} - uv\frac{\partial v}{\partial y}\right)$$
- vertical wind shear: Sv=
$$\sqrt{\left(\frac{\partial u}{\partial p}\right)^2 + \left(\frac{\partial v}{\partial p}\right)^2}$$

11. FIGURES

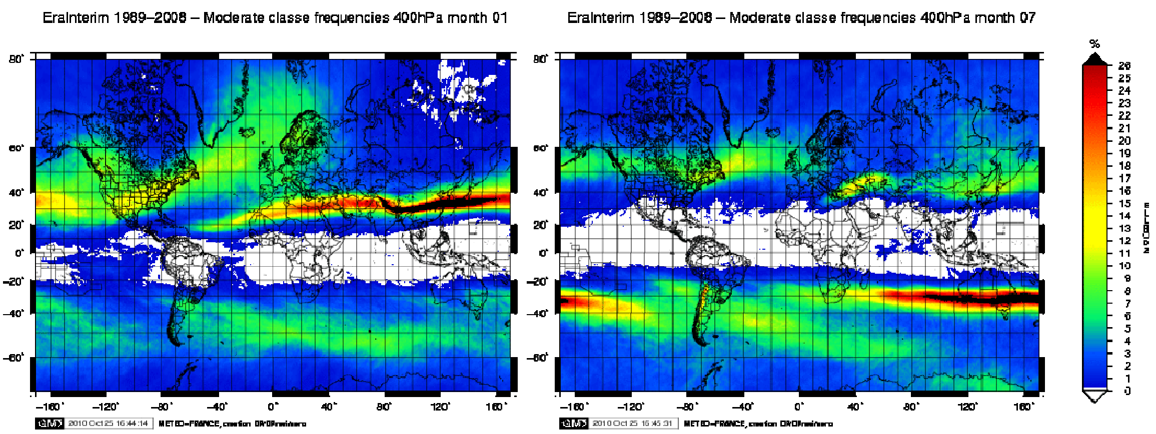

Figure 1: Climatology of ELLROD2 CAT index at global scale at 400hPa, frequency of the moderate class, for January on the left and July on the right.

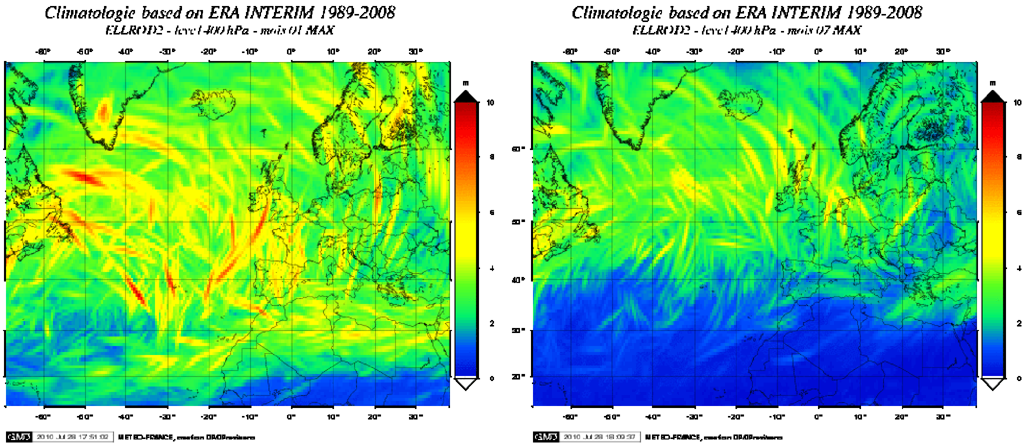

Figure 2: Climatology of ELLROD2 CAT index at global scale at 400hPa, maximum values, scale from 0 to 10.10-^{6} sec^{-2}, for January on the left and July on the right. The most severe events are well represented.

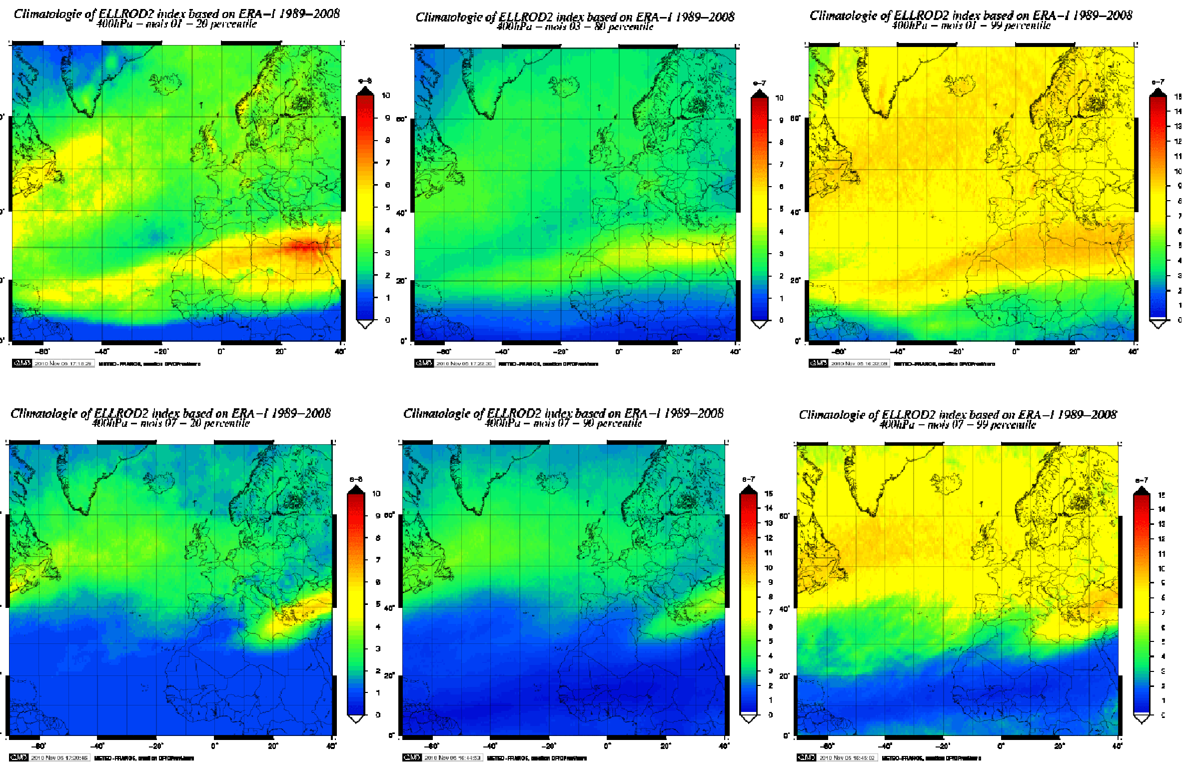

Figure 3: Climatology of ELLROD2 CAT index on Europe at 400hPa, 20% percentile on the right (scale 0 to 10e^{-8}), 90% percentile in the middle (scale 0 to 10e^{-7}), and 99% percentile on the left (scale 0 to 15e^{-7}) for January on the top and July on the bottom.

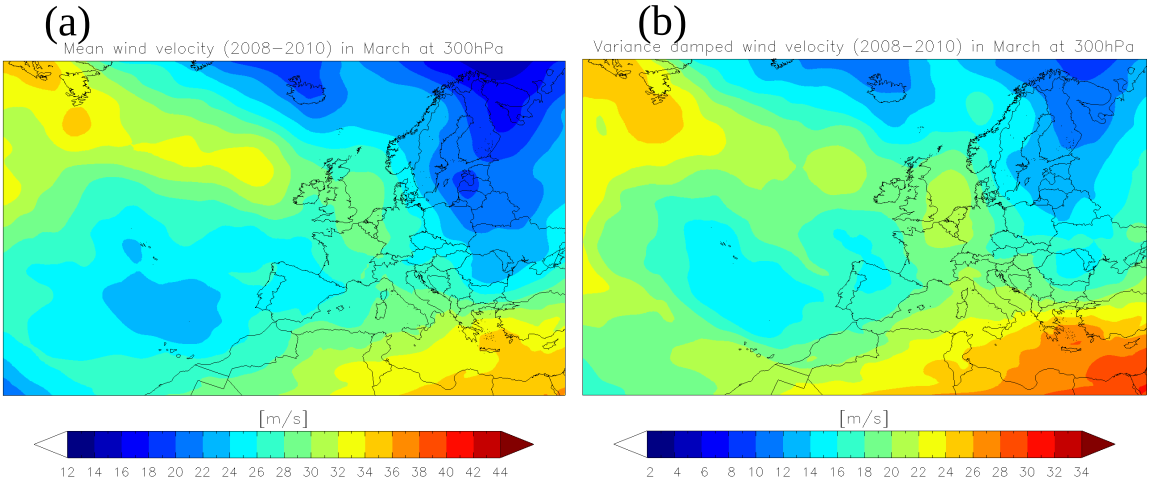

Figure 4: Comparison of mean wind velocity (a) and (b) variance damped wind velocity for March

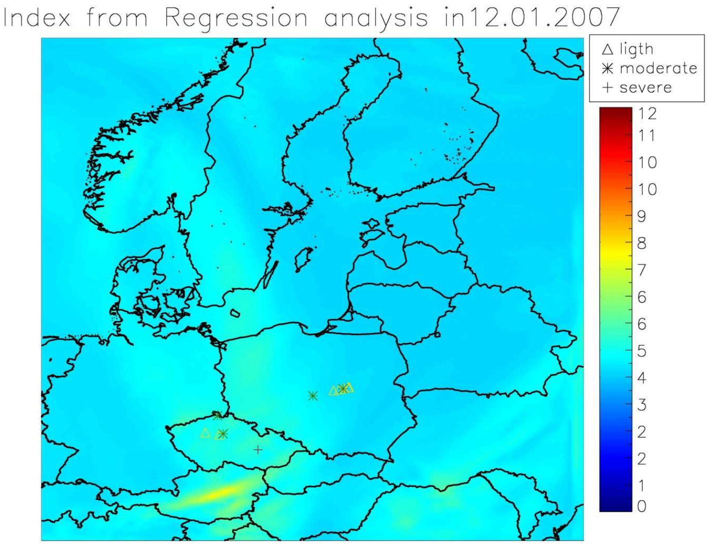

Figure 5: Example of regression index with AMDAR overlay